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Evidence for a Supernova Associated with the X-ray Flash 020903[1]

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ABSTRACT

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We present ground-based and *Hubble Space Telescope* optical observations of the X-ray flash (XRF) 020903, covering 300 days. The afterglow showed a very rapid rise in the first day, followed by a relatively slow decay in the next few days. There was a clear bump in the light curve after ~ 25 days, accompanied by a drastic change in the spectral energy distribution. The light curve and the spectral energy distribution are naturally interpreted as the emergence – and subsequent decay – of a supernova (SN), similar to SN 1998bw. At peak luminosity, the SN is estimated to be 0.8 ± 0.1 mag fainter than SN 1998bw. This argues in favor of the existence of a supernova associated with this X-ray flash. A spectrum obtained 35 days after the burst shows emission lines from the host galaxy. We use this spectrum to put an upper limit on the oxygen abundance of the host at [O/H]≤ -0.6 dex. We also discuss a possible trend between the softness of several bursts and the early behavior of the optical afterglow, in the sense that XRFs and X-ray rich GRBs seem to have a plateau phase or even a rising light curve. This can be naturally explained in models where XRFs are similar to GRBs but seen off the jet axis.

Subject headings: gamma-ray bursts — supernovae

1. Introduction

X-ray flashes (XRFs) are bursts of high-energy light whose properties are similar to those of gamma-ray bursts (GRBs): they are transient events of short duration (typically a minute), distributed isotropically on the sky, and have fluences, frequencies (number per day), and spectra comparable to those of GRBs (Heise 2003; Kippen et al. 2003). Their spectra are similar to those of GRBs but their peak energies in the νF_ν spectrum, $E_{\rm peak}$, are smaller than those of GRBs (Heise 2003; Kippen et al. 2003; Sakamoto et al. 2005). In various respects, XRFs seem to be a low-energy extension of GRBs. In light of these similarities, it is tempting to try to unify these classes of events into a single framework (e.g., Lamb, Donaghy, & Graziani, 2004, and references therein). Differences between XRFs and GRBs may be intrinsic, caused for instance by different Lorentz factor (Barraud et al.

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2005) or by a high baryon load (Dermer, Chiang, & Böttcher 1999). They might be extrinsic; in particular the observed properties are determined by the viewing angle (Yamazaki, Ioka, & Nakamura 2002, 2004; Granot et al. 2005).

The redshift of XRF 020903 ($z = 0.251$; Soderberg et al., 2004; this paper) clearly shows that XRFs are cosmic explosions of phenomenal power, almost comparable to GRBs. The isotropic energy of this XRF is very large (1.1×10^{49} erg) though not as large as that of typical GRBs (up to 10^{54} erg; see Bloom, Frail & Kulkarni, 2003). The similarities and differences between XRFs and GRBs will hopefully help us elucidate the nature of these events and perhaps find a common model describing both phenomena.

One obvious requirement for a unified model is that both types of event (XRFS and GRBs) have the same kind of progenitor. For gamma-ray bursts it is now clear that they are associated with core-collapse supernovae (SN) of type Ib/c. This GRB/SN connection has received more and more support over the years. Some theoretical models (e.g. Woosley, 1993; see Zhang, Woosley, & Heger, 2004, for recent developments) predict such a connection for GRBs and XRFs, but it is only with GRB 980425 that observations showed the first hint of this association (Galama et al. 1998). The bump on the light curve of GRB 011121 and its rapid color evolution (e.g. Garnavich et al. 2003) provided strong evidence in favor of this genetic link between GRBs and SNe. There have been other GRBs with "bumps" ("bump" is here defined as a rebrightening observed 15-20 days after the burst) in their light curves that could be attributed to SNe but none were as definitive as GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003); the spectrum of this burst showed features that could only be explained with the existence of an underlying Type Ib/c SN. Later, Malesani et al. (2004) presented spectroscopic evidence for the existence of a SN associated with GRB 031203. In cases where a SN could have been detected, there was indeed a bump on the light curve (See Zeh et al, 2004, and references therein).

When it comes to XRFs however, the situation is less clear. Soderberg et al. (2005a) presented for several X-ray flashes. Although the conclusions of their study are limited by the fact that some objects do not have a measured redshift, they do detect supernova signatures in some cases. In contrast, they also put strong upper limits on the brightness of any possible SN associated with some of the events they studied. Fynbo et al. (2004) showed that XRF 030723 actually had a strong bump on its light curve that could be fit reasonably well with the light curve of SN 1994I. At the time of the bump the energy distribution was very red and was not consistent with a power law. Furthermore, Levan et al. (2005a) report a non-detection of supernova features in the light curves of XRF 011030 and XRF 020427. All one can say from these works is that if XRFs are associated with SNe, they cover a large range in peak magnitude. It is thus necessary to observe XRFs thoroughly and determine

the peak magnitude of any SN associated with these events.

The burst XRF 020903 was detected by the *High Energy Transient Explorer 2* (HETE-2) on 3 September 2002 at 10:05:38 (Ricker et al. 2002). Optical observations started within a few hours after the burst. Initially no afterglow was detected (Tristram et al. 2002; Price et al. 2002; Pavlenko et al. 2002; Uemura et al. 2002). Images taken 6 d apart on the Cerro Tololo Inter-American Observatory (CTIO) Blanco 4 m telescope did not show an obvious variable source (Fruchter et al. 2002). The analysis we present here shows that the optical transient (OT) varied very little between these two epochs. Using data obtained on 4 September and 10 September 2002, Soderberg et al. (2002) reported (26 days after the burst) the discovery of an optical afterglow. From optical spectroscopy obtained on 28 September 2002, Soderberg et al. (2002) measured a redshift $z = 0.25$; this was the first reported redshift for an XRF. A fading radio source was also discovered (at the position $\alpha_{2000} = 22^h48^m42\overset{s}{.}339$, $\delta_{2000} = -20°46'08\overset{''}{.}95$, Soderberg et al. 2002, as updated by Soderberg et al. 2004), indicating an association with XRF 020903. After about 30 days, there was no variability observed in the optical (Covino et al. 2002; Gorosabel et al. 2002), presumably because of the bright host galaxy. Further *Hubble Space Telescope* (*HST*) observations (Levan et al. 2002) showed that the source was actually still fading.

Sakamoto et al. (2004) showed that the peak energy, $E_{\rm peak}$, of XRF 020903 was very low, below ~ 3 keV. From the redshift and observed fluence, the equivalent isotropic energy, $E_{\rm iso}$, was 1.1×10^{49} erg. Furthermore, there was no detected emission beyond 10 keV. XRF 020903 is thus one of the most extreme X-ray flashes observed by HETE-2 (see Sakamoto et al. 2005, for a general discussion of GRBs and XRFs found by HETE-2).

We obtained data on XRF 020903 using ground-based telescopes and the *Hubble Space Telescope* (*HST*); these observations are presented in Sect. 2. In Sect. 3, we discuss the light curve and the spectral energy distribution; we also present a spectrum of the host galaxy and determine an upper limit on its oxygen abundance. We discuss our findings in Sect. 4.

2. Observations and Photometry

2.1. Ground-Based Data

We obtained BRI data ~ 0.6 d after the burst with the wide-field MOSAIC II camera on the CTIO Blanco 4 m telescope. We secured another R-band observation with this telescope 5.7 d after the burst. We also have R-band data, observed on 29 Sep 2002 with the Asiago Faint Object Spectrograph and Camera (AFOSC) on the 1.82 m "Copernicus" telescope at Mt Ekar (Asiago, Italy), and we have VRI data taken on 2 October 2002 with

the 3.6 m Telescopio Nazionale Galileo (TNG) at La Palma, where we used the DOLoRes camera (Conconi et al. 2001). A preliminary analysis of these TNG and Asiago data has been given by Covino et al. (2002). Between 10 and 14 October 2002, and then on 26 October, we obtained $BVRI$ data with the Danish 1.5 m telescope at La Silla Observatory (Gorosabel et al. 2002).

Given that the OT is located in a fairly bright host (see Fig. 1), the ground-based photometry is delicate. In order to remove the contribution of the host galaxy, we used the image convolution and subtraction methods of Alard (2000; see also Alard & Lupton 1998). To fully exploit this method one needs a reference image where the optical transient has faded well below the detection limit. We thus secured late-time images in August 2004 with the CTIO 4 m telescope (in RI), and with the Danish 1.5 m telescope (in BV). These images have been used as templates in the image subtraction method. We then performed aperture photometry on each subtracted frame. The absolute calibration was done using secondary standards from the list of Henden (2002). Our photometry is presented in Table 1.

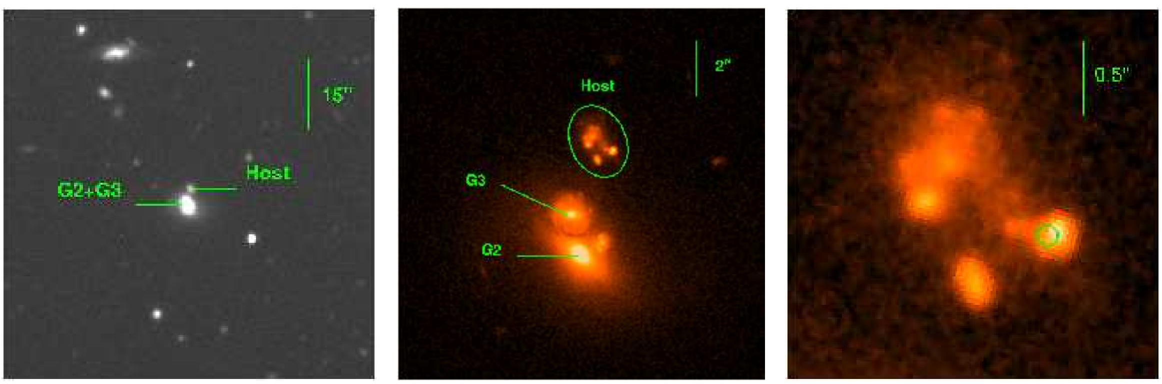

Fig. 1.— *(Left panel)* CTIO R-band image of the area around XRF 020903. North is up, east is to the left. The host is the small galaxy near the center of the image. The galaxies G2 and G3 are not resolved in our ground-based images. *(Center panel)* *HST* image showing the host (the cluster of knots in the upper part of the image), and the nearby galaxies G2 and G3. *(Right panel)* *HST* image showing in detail the complex structure of the host. The $0''.1$ circle is centered on the position of the OT.

2.2. *Hubble Space Telescope* Data

We obtained data at three epochs (95, 232, and 301 days after the burst) with *HST*, using the Advanced Camera for Surveys (ACS) and the F606W filter (Levan et al. 2002). The images were reduced and drizzled in a standard manner (Fruchter & Hook 2002). The pixel scale of the final images is $0\farcs033$, 2/3 of the native ACS scale ($0\farcs05$). The first- and second-epoch images were then aligned with the third-epoch image. Subtracting the third image from the first epoch gave a clear detection of the OT, and a very accurate position.

Given the brightness of the OT after ~ 35 days, it is possible that, for a plausible decay rate, the OT might still be contributing to the total light observed during the third *HST* epoch (after 301 days, for an exposure time of 3840 seconds). To test this, we measured the fluxes in a small aperture on the three original images (i.e., not subtracted) at the position of the OT; the total flux thus contained the contribution of the host galaxy within this aperture. We fitted an exponential decline rate plus constant to the three *HST* fluxes (fitting a power law yields the same result)

$$F(t) = A\exp(-t/B) + C$$

The parameters are the half-life, normalization, and host flux within the aperture. It turned out that the fitted flux of the host within the aperture (the parameter C) was smaller than the flux measured for the third epoch. This means that indeed, the OT was contributing some light during the third epoch. The consequence is that when we subtracted the third epoch from the first and second epochs, we introduced a bias in the sense that we subtracted too much light, since the OT was still contributing in the third epoch, used as reference. This is almost inconsequential for the first epoch but it is a significant fraction of the total OT flux in the second epoch.

To correct for this over-subtraction, we assumed that the decay was exponential[2]. The measured and corrected magnitudes are given in Table 2. We find that the decay rate is 0.0167 mag/day, corresponding to an exponential decay time of about 60 d. This is intermediate between the B- and V-band decay of SN 1998bw (0.0141 and 0.0184 mag/day respectively; McKenzie & Schaefer 1999). These magnitudes are in the F606W filter which

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[2]The method used for this correction is as follows. We measured fluxes on the subtracted images, f_1 and f_2; these are the over-subtracted fluxes. The OT flux on the third image is unknown. The *true* fluxes are denoted F_1, F_2, and F_3. These fluxes satisfy the conditions $f_1 = F_1 - F_3$ and $f_2 = F_2 - F_3$. We assume that the flux decays as $F(t) \propto \exp(-t/\tau)$. In essence, the method is not different from a non-linear χ^2 fit: if we assume we know F_1 and the decay rate, we can then compute F_2 and F_3. From this we can compute f_1 and f_2. If these computed values are equal to the observed values, we have found the solution; if not, we iterate the procedure with new values of F_1 and the decay rate until we reach agreement

Table 1: Ground-based photometry of XRF 020903[a] .

UT date	Time after burst (d)	Telescope[b]	Filter	mag	$\sigma_{\rm mag}$
2002 Sep 04.115	0.695	CTIO 4m	B	21.40	0.17
2002 Oct 10.177	36.757	DK 1.5m	B	24.59	0.26
2002 Oct 11.193	37.772	DK 1.5m	B	24.76	0.31
2002 Oct 12.169	38.749	DK 1.5m	B	24.77	0.32
2002 Oct 13.163	39.743	DK 1.5m	B	>24.5	-
2002 Oct 14.137	40.716	DK 1.5m	B	>24.4	-
2002 Oct 02.953	29.533	TNG	V	>22.8	-
2002 Oct 10.192	36.772	DK 1.5m	V	>23.4	-
2002 Oct 11.7[c]	38.279	DK 1.5m	V	23.45	0.21
2002 Oct 13.179	39.758	DK 1.5m	V	>23.2	-
2002 Oct 14.152	40.731	DK 1.5m	V	>23.1	-
2002 Sep 04.080	0.660	CTIO 4m	R	20.858	0.007
2002 Sep 04.32[d]	0.900	Palomar 5m	R	19.52	0.22
2002 Sep 09.130	5.709	CTIO 4m	R	21.129	0.010
2002 Sep 10.30[d]	6.880	Palomar 5m	R	21.80	0.30
2002 Sep 29.923	26.503	Asiago	R	21.729	0.089
2002 Oct 2.967	29.547	TNG	R	21.552	0.044
2002 Oct 10.204	36.783	DK 1.5m	R	22.351	0.051
2002 Oct 11.216	37.796	DK 1.5m	R	22.279	0.052
2002 Oct 12.193	38.772	DK 1.5m	R	22.450	0.055
2002 Oct 13.187	39.766	DK 1.5m	R	22.522	0.054
2002 Oct 14.110	40.689	DK 1.5m	R	22.498	0.065
2002 Oct 26.062	52.641	DK 1.5m	R	23.032	0.087
2002 Sep 04.107	0.686	CTIO 4m	I	20.425	0.015
2002 Oct 02.977	29.556	TNG	I	20.916	0.062
2002 Oct 10.172	36.752	DK 1.5m	I	21.430	0.064
2002 Oct 12.201	38.780	DK 1.5m	I	21.442	0.060
2002 Oct 13.071	39.651	DK 1.5m	I	21.495	0.057

[a]This is the photometry of the OT only, after subtraction of the host galaxy.

[b]The key to telescope identification is as follows: CTIO 4m = Cerro Tololo 4 m, DK 1.5m = 1.5 m Danish telescope at La Silla, TNG = 3.6 m Telescopio Nazionale Galileo at La Palma, Asiago = 1.8 m telescope at Mt Ekar, Palomar 5m = Mt Palomar 5 m Hale telescope.

[c]Average of two measurements on Oct 11 and Oct 12.

[d]From Soderberg et al. (2004), after having subtracted the contribution from the host galaxy (see text for details). Note that these data have been re-examined by Soderberg et al. (2005a) where they use image subtraction. According to their Figure 2, the measurement at ~ 6.9 d is ~ 21.8 mag, the value we use here.

Note. — The data in this table supersede the data presented by Fruchter et al. (2002); Gorosabel et al. (2002), and Levan et al. (2002).

corresponds to a rest-frame wavelength of about 4900 Å. Since this is about half-way between the effective wavelengths of the B and V filters, one can conclude that the decay of XRF 020903 is very similar to that of SN 1998bw.

As described below (Sec. 3), the spectral energy distribution (SED) evolved considerably between 6 and 38 days, but at the time of our *HST* observations we have no color information. In order to facilitate the comparison of the *HST* data with other data, we transformed our observations in the F606W filter to the R band. We used the IRAF[3]/synphot task to do this, assuming that the SED is a power law, $F_\nu \propto \nu^\beta$ (this assumption is valid given the small wavelength range we need to consider for this procedure). We took a power-law index $\beta = -4$, as it represents well the last SED observed (at 38 d, see Sec. 3.1). Table 2 gives the magnitudes we found after correcting the F606W data to R band.

3. Light Curve and Discussion

3.1. The Spectral Energy Distribution

We could determine the SED at two epochs, at 0.68 d and at 38.6 d after the burst (see Fig. 2). We used magnitude zero points from Fukugita et al. (1995). We corrected the fluxes for foreground extinction, using a color excess $E(B-V) = 0.033$ mag from Schlegel et al. (1998). At 0.68 d, the SED is well fitted by a power law of index $\beta = -0.49 \pm 0.07$ (where $F_\nu \propto \nu^\beta$).

The striking feature of Figure 2 is the change in the shape of the energy distribution. At 38.6 d the SED was very red. A formal power-law fit to the SED gives an exponent $\beta = -4.10 \pm 0.29$. There is, however, some noticeable curvature in the SED. In this respect, the behavior of XRF 020903 resembles that of another XRF, 030723 (Fynbo et al. 2004), whose SED was well represented by a power law in the first few days but after ~ 3 weeks it had a strong curvature. Figure 2 also shows that at 38.6 d the SED resembled that of local stripped-envelope core-collapse supernovae such as SN 1998bw and SN 1993J, although with less curvature.

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[3]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2: Photometry of *HST* data.

UT date	Time after burst (days)	mag[a] F606W	σ (mag)	mag[b] F606W	mag[c] R
2002 Dec 03.792	95.426	24.28	0.05	24.23	23.81
2003 Apr 23.955	232.824	27.00	0.12	26.53	26.11
2003 Jun 30.652	300.625	···	0.20	27.66	27.24

[a]Measured in the subtracted images.

[b]These magnitudes have been corrected for over-subtraction (see text).

[c]R-band magnitudes, from F606W, assuming that the SED is a power law ($F_\nu \propto \nu^\beta$) of index $\beta = -4$. The uncertainties in these magnitudes are the same as for the F606W measurements.

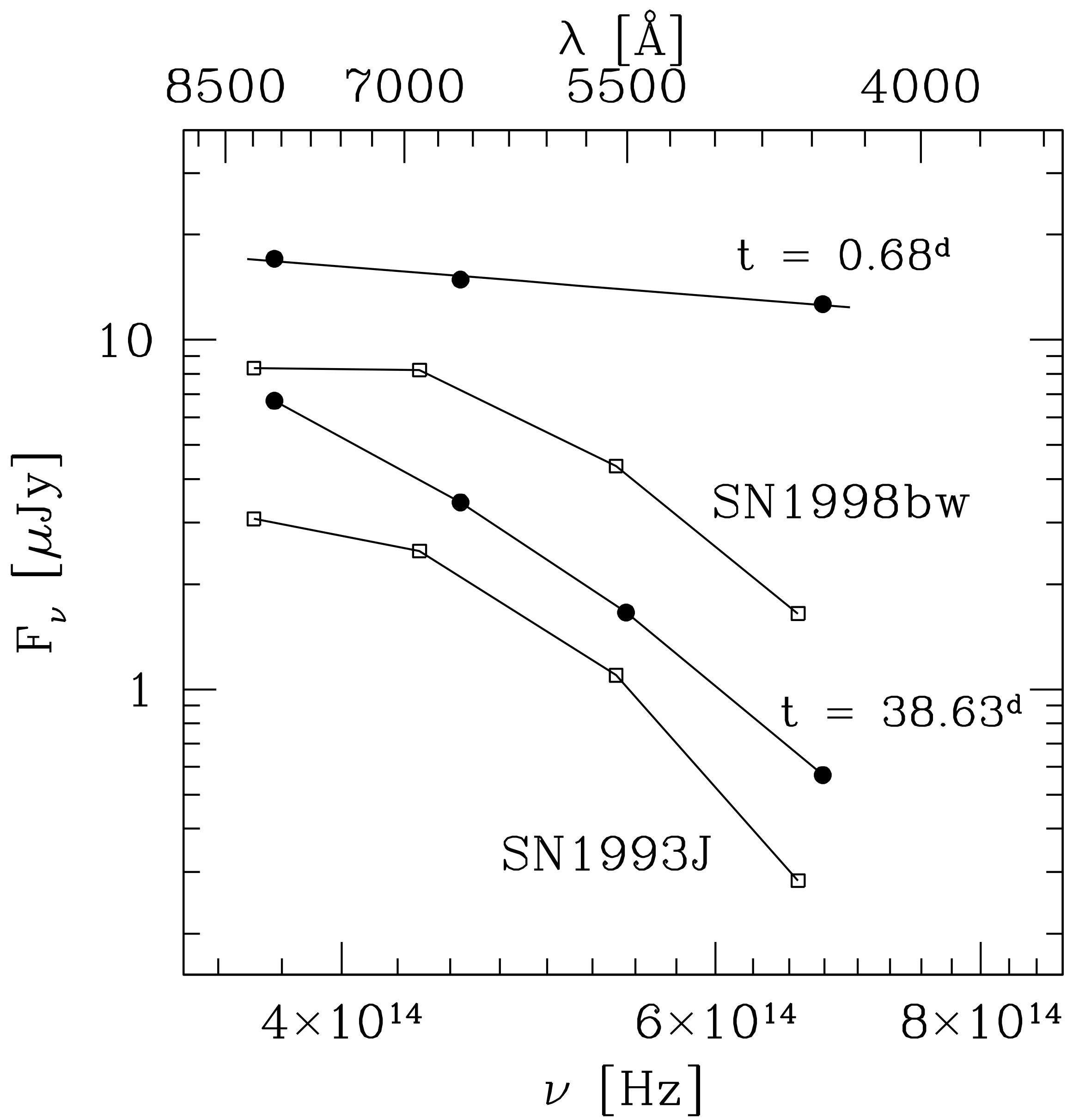

Fig. 2.— Spectral energy distribution at 0.68 d and at 38.6 d. The data (black dots) have been corrected for foreground reddening. The solid line at $t = 0.68$ d is a power-law fit. The open squares are the $UBVR$ data of two local supernovae, SN 1998bw (at 30.7 d in the rest frame) and SN 1993J (at 30.3 d in the rest frame), appropriately redshifted to $z = 0.25$ and corrected for their respective reddening (Patat et al. 2001; Richmond et al. 1996a).

3.2. Early Light Curve

To the data described in Sec. 2, we added two measurements from Soderberg et al. (2004) in order to fill the large gap in the time coverage of this burst. We subtracted the magnitude of the host galaxy (see Sect. 3.4) from their data in order to determine the brightness of the OT. Their last few data points are fairly noisy and the OT contributed very little light. The resulting light curve is presented in Fig. 3.

There are upper limits on the brightness of the afterglow from several early searches (Tristram et al. 2002; Price et al. 2002; Pavlenko et al. 2002; Uemura et al. 2002). This might be explained when one considers the combination of the Palomar 200" data (Soderberg et al. 2004) with ours: we see that there was an initial rise, particularly marked between our first epoch (0.68 d) and the first observations at Palomar after 0.9 d. Early on the afterglow was too faint to be seen. Assuming that the rise follows a power law ($F(t) \propto t^{\alpha}$), the index is +4.

Several other bursts show this kind of behavior early on (a fast rise, sometimes preceded by a relatively flat phase). For instance, GRB 970508 had a "plateau" after which it rose by ~ 1.5 mag within ~ 0.4 day before decaying according to a power law (Castro-Tirado et al. 1998; Pedersen et al. 1998; Pian et al. 1998). It turns out that GRB 970508 is an X-ray rich burst close to the XRF regime (this is obtained from the integration of the spectrum given by Amati et al. 2002). GRB 030418 is also an X-ray rich GRB (Sakamoto et al. 2005) whose afterglow rose during the first $\sim$ half hour (Rykoff et al. 2004). Another X-ray rich burst, GRB 041006, had a very shallow early decay (see the data compilation in Granot et al., 2005). The afterglow of GRB 030723, an XRF, had an almost flat light curve during most of the first day.

All these soft bursts seem to show a trend between the softness of the prompt emission and the early decay rate of the afterglow. From a theoretical point of view, Granot et al. (2002) and Granot & Kumar (2003) show that, depending on the viewing angle it is possible to have a rapidly rising afterglow, such as is observed for XRF 020903. In the models of Granot & Kumar (2003) and Granot et al. (2005) the shape of the light curve is determined in particular by the opening angle of the jet, the viewing angle (or rather, the relation between these two angles), and the angular distribution of energy across the jet. In their model, X-ray flashes are seen off-axis, i.e., the viewing angle is larger than the opening angle of the jet. Using this approach, Granot et al. (2005) can reproduce the light curves of XRF 030723 and GRB 041006 fairly well. For XRF 020903, we can say in particular that in order to have a fast rise, one needs a jet with a very sharp edge (Granot & Kumar 2003; Granot et al. 2005).

Because of the large gap between 0.9 d and 5.7 d after the burst, it is impossible to know when the OT reached its maximum brightness. It is equally impossible to know its decay rate. If we assume that the OT reached maximum brightness at 0.9 d and also assume that it subsequently decayed following a power-law ($f(t) \propto t^{\alpha}$), then the index is $\alpha = -0.8$ in this 5 day time interval. If the afterglow continued to rise after 0.9 d then the later decay will be faster than -0.8. Given the paucity of data in the first week, we cannot rule a more complex behavior of the afterglow. In particular, the second Palomar 5m data point at 6.9 d implies a faster decay (although this measurement has a large uncertainty).

For some late-time images (obtained later than 25 days after the burst), particularly in the B and V passbands, the optical transient was not detected in the subtracted frames, we could only set upper limits to the magnitudes (see Table 1). From R band data one can nevertheless say that the OT must have decayed very slowly between 6 and 26 d. After that time it became fainter at a fast rate. This decay continued at least until 300 d after the burst, as evidenced by the *HST* data (see Fig. 3).

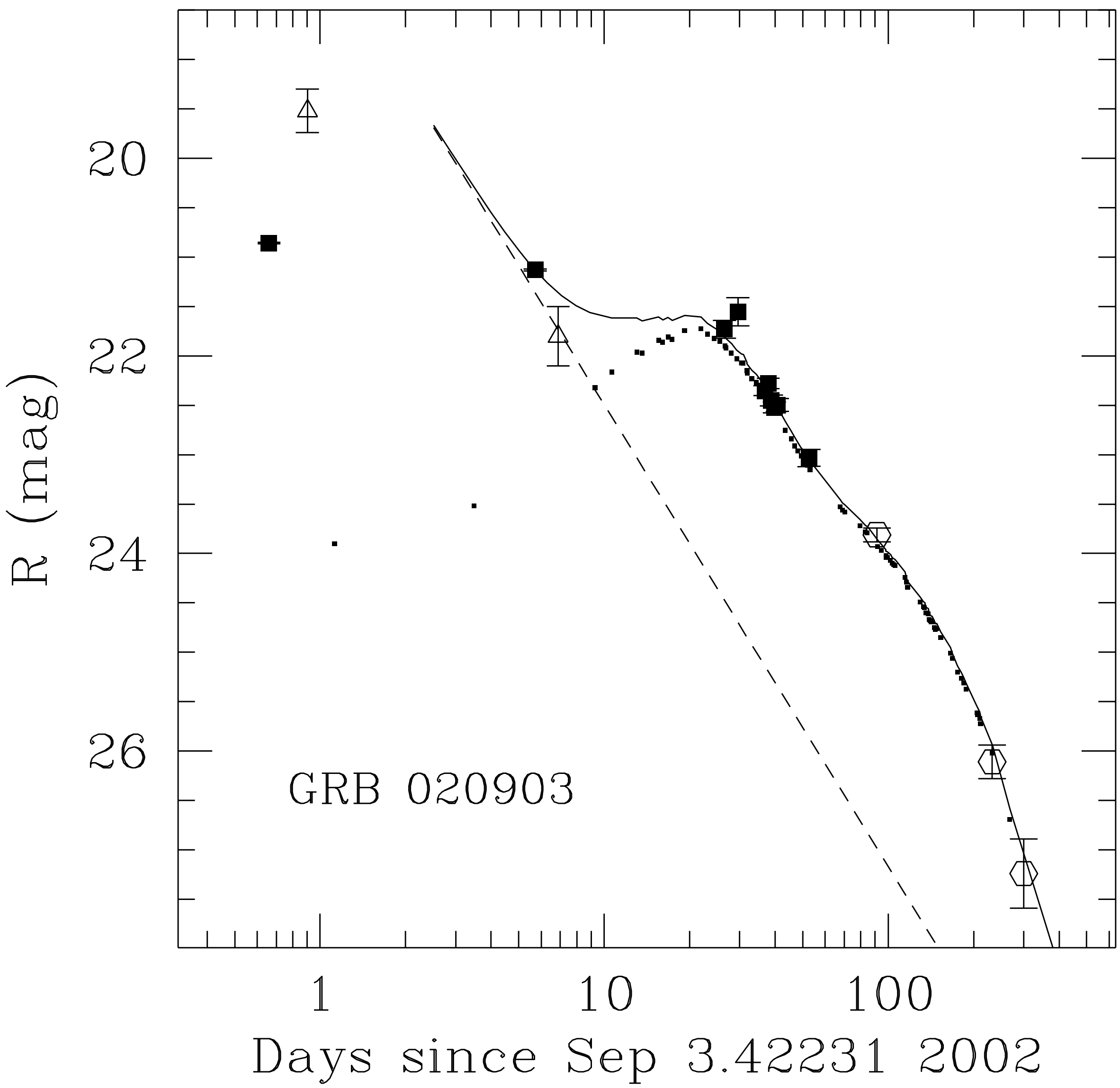

Fig. 3.— *R*-band light curve of XRF 020903. Solid squares are our ground-based data reported here, open triangles are the Palomar 5m measurements (Soderberg et al. 2004) after subtraction of the host galaxy flux (see text for details), open hexagons (after 95 days) are *HST* F606W measurements transformed to the *R* band (see text for details on this transformation). The small black dots are the *V*-band light curve of SN 1998bw, corrected for reddening (Patat et al. 2001), redshifted (to account for cosmological time dilation) then shifted by 0.8 mag (fainter). The solid line is the sum of a power law of index −1.87 (dashed line) and SN 1998bw shifted by 0.8 mag.

3.3. Late-Time Light Curve

The OT decayed by ~ 0.5 mag between 5 d and 26 d, after which the flux decreased at a faster rate. Figure 3 shows that a simple broken power-law model will fail to describe the light curve; the addition of a supernova component is necessary to fit the late-time bump. For the fit, we corrected the magnitudes for the foreground reddening. The SN 1998bw data were also corrected for the reddening using the value of Patat et al. (2001).

We tried to reproduce the light curve by fitting a combination of power law (with two free parameters - decay index and flux normalisation), and shifted SN 1998bw light curve (adding two more free parameters - magnitude shift and time stretch factor; see e.g. Zeh et al., 2004). Concentrating on the data obtained after 5 days, the fit yields the following results: the power law has an index equal to $\alpha = -1.87 \pm 0.28$; the supernova light curve is that of SN 1998bw in the V band[4] shifted by 0.8 ± 0.08 mag (fainter). A stretch factor was also applied to the SN light curve although it does not appear necessary (1.0 ± 0.03).

We tried other SN light curves, in particular those of SN Ib 1993J (Richmond et al. 1996a) and SN Ic 1994I (Richmond et al. 1996b). Both gave substantially poorer fits than SN 1998bw. We conclude that the supernova associated with XRF 020903 was very similar to SN 1998bw, except that it was fainter and redder (see Fig. 2). The SN could actually be brighter than the limit derived above if there is some internal reddening. These results are consistent with, but more precise than, those of Soderberg et al. (2005a). They found that the supernova is 0.6 ± 0.5 mag fainter than SN 1998bw, and that the SN light curve had to be "compressed", i.e., a faster decay than SN 1998bw. We believe that our better photometry (obtained via image subtraction, as opposed to simply extracted from the GRB Coordinates Network Circulars), and the correction of *HST* data for over-subtraction explain these differences.

Several supernovae associated with GRBs are sufficiently well characterized (see, e.g., Zeh et al. 2004) that one can plot the SN luminosity (in units of SN 1998bw) versus the SN decay time. Stanek et al. (2005) hinted at a correlation between these two quantities. With a luminosity ratio of ~ 0.5 and a stretch factor of 1, the SN associated with XRF 020903 adds to the dispersion in this plot, and does not follow the trend seen for Type Ia SNe (Phillips 1993). A large amount of reddening ($E(B-V) \sim 0.25$) would bring this SN in line with the trend but there is no evidence for this amount of reddening. Actually, with $E(B-V) = 0.165$, the reddening-corrected SED at 0.68 d would be flat (slope=0). We

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[4]We used the V-band light curve of SN 1998bw because at a redshift of 0.251, the observed R band is almost exactly equal to the rest-frame V band.

consequently take this value of $E(B-V)$ as a strong upper limit. Were the reddening so large (0.165), then the SN brightness at maximum would only be 0.3 mag fainter than SN 1998bw. As noted above however, this is very strong upper limit and this transform into a strong upper limit on the peak magnitude of the SN associated with XRF 020903.

3.4. The Host Galaxy

BVRI host magnitudes (see Table 3) were obtained from late-time ground-based images. Even though these images were obtained in good seeing conditions, one should be aware that the host is at best marginally resolved; we can not distinguish the various knots seen in the right panel of Fig. 1. Our host magnitudes are in good agreement with values reported in the Gamma ray bursts Coordinates Network (GCN) after accounting for the non-negligible fraction of the light coming from the OT in the GCN magnitudes (Covino et al. 2002; Gorosabel et al. 2002). In particular, our R-band magnitude is very close to that given by Soderberg et al. (2004). The uncertainties in the host magnitudes are large because of the presence of the complex of galaxies "G2+G3" which contaminates the photometry in ground-based data. The fact that photometry is delicate can also be inferred from the dispersion in the magnitudes in Covino et al. (2002) and Gorosabel et al. (2002). We conservatively estimate our host photometry uncertainties to be ±0.1 mag.

3.5. Spectroscopy

A spectrum was obtained on 8.4 October 2002 (35 d after the burst) using the Keck-I telescope and the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995). We used the 400/3400 grism on the blue side; on the red side we used the 400/8400 grating.

Table 3: Photometry of the host galaxy.

UT date	Telescope[a]	Filter	mag	σ (mag)
2004 Aug 24.259	DK 1.5m	B	21.7	0.1
2004 Aug 22.278	DK 1.5m	V	20.8	0.1
2004 Sep 14.032	CTIO 4m	R	20.8	0.1
2004 Sep 14.059	CTIO 4m	I	20.5	0.1

[a]DK 1.5 = 1.5 m Danish telescope at La Silla, CTIO 4m = Cerro Tololo 4 m

The slit width was $1''$, aligned at a position angle of 162.6°, which was the parallactic angle (Filippenko 1982) at the time of the observations. We obtained two exposures, one of 1250 s and the other of 1800 s. The conditions were poor, making the absolute flux calibration quite uncertain, although relative fluxes should be little affected.

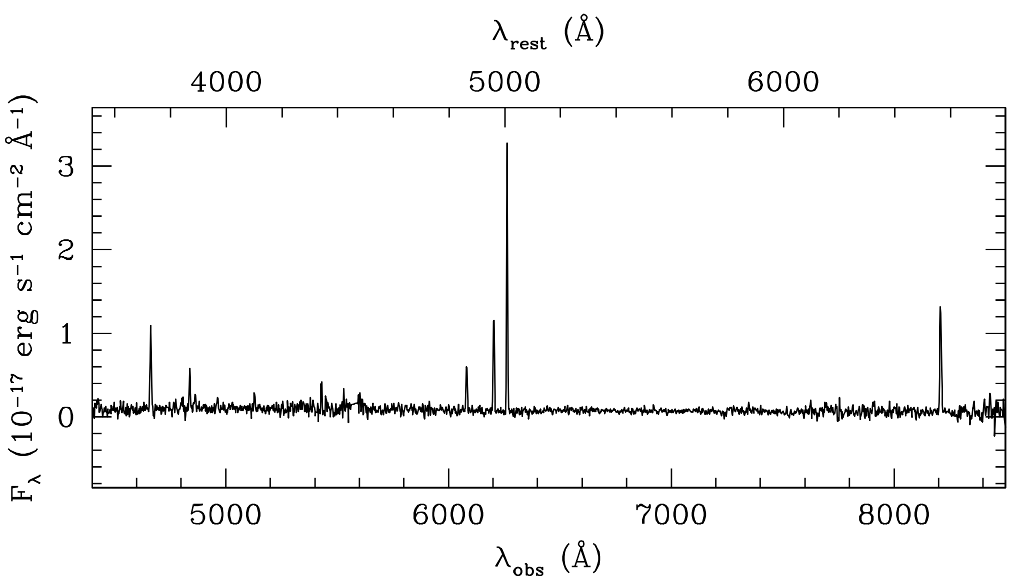

Fig. 4.— Keck spectrum of the host of XRF 020903. We detect strong emission lines associated with star formation in a low-metallicity environment. The fluxes have been corrected for foreground extinction.

We clearly detect several lines associated with strong, on-going star formation, [O II] λ3727, [Ne III] λ3867, hydrogen Balmer lines, and [O III] $\lambda\lambda$4959, 5007. Several common lines are not detected, in particular [N II] $\lambda\lambda$6548, 6583. Before measuring fluxes, we corrected the spectrum for the small foreground reddening, $E(B-V) = 0.033$ mag (Schlegel et al. 1998). Fluxes and equivalent widths were then measured by fitting a Gaussian to the line profiles, and the results are given in Table 4. Using eight strong lines, we measured a redshift $z = 0.2506 \pm 0.0003$, in agreement with the value determined by Soderberg et al. (2004).

Table 4: Emission line fluxes.

Ion	Wavelength $\lambda_{\rm obs}$ (Å)	Flux f	$f/f_{H\beta}$	Equivalent width $\mathrm{EW}_{\rm rest}$ (Å)
[O II]	4663.52	7.982	2.274	−68.96
[Ne III]	4838.76	2.923	0.833	−24.47
[Ne III]	4963.32	1.059	0.302	−8.67
Hδ	5129.45	1.272	0.362	−10.12
Hγ	5430.13	2.019	0.575	−15.94
Hβ	6081.46	3.510	1.000	−36.08
[O III]	6203.46	7.386	2.104	−77.44
[O III]	6263.21	20.89	5.952	−221.16
Hα	8208.78	11.46	3.265	−152.40
[N II]	8239.60	< 0.133	–	–

Note. — Fluxes are in units of 10^{-17} erg s^{-1} cm^{-2}. They have been corrected for foreground reddening (using $E(B-V) = 0.033$, see Sect. 3.1). Equivalent widths have been corrected to the rest frame.

We set out to determine the metallicity of the host galaxy from the emission-line ratio R_{23}, following the procedure outlined in Kewley & Dopita (2002) as updated in Kobulnicky & Kewley (2004). This ratio is defined as $R_{23} \equiv (I_{[\text{O II}]\lambda3727} + I_{[\text{O III}]\lambda4959} + I_{[\text{O III}]\lambda5007})/I_{\text{H}\beta}$. Using the values in Table 4, we find $\log R_{23} = 1.014$. This is beyond the range of values for which the R_{23} method has been calibrated (see, e.g., Kewley & Dopita 2002; Kobulnicky & Kewley 2004). Consequently, we cannot use the R_{23} ratio to determine an accurate abundance.

There are several possible reasons explaining why the R_{23} ratio is high. One is that the average density in the host of XRF 020903 is higher than in the models of Kewley & Dopita (2002). This is sometimes observed for Lyman-break galaxies (L. Kewley, 2005, private communication). Another reason is that the excitation process may not be purely due to photoionization. In particular, shock excitation would change the line ratios, seriously compromising the R_{23} method. We can nevertheless obtain an upper limit on the abundance [O/H], using the fact that the [N II] $\lambda6583$ line is not detected. We estimated the average noise (σ) in the wavelength region around this line, and took the upper limit on the line flux as $3\sigma = 1.33 \times 10^{-18}$ erg s^{-1} cm^{-2}. From the ratio of $\log([\text{N II}]/\text{H}\alpha) \leq -2.02$, we obtain an upper limit on the abundance, namely $[\text{O/H}] \leq -0.6$ dex (see Figure 7 of Kewley & Dopita 2002).

4. Conclusions

The early afterglow of XRF 020903 behaved rather unexpectedly, as it rose in the first day. This type of time evolution has already been seen in a few other GRB/XRF afterglows. Some models can actually reproduce this behavior. In particular, Granot et al. (2005) attribute this to the fact that the burst is seen away from the symmetry axis of the jet (Sec. 3.2). A rising light curve is a prediction of the off-axis model and it is interesting to note that, as the most extreme object of this class, XRF 020903 also has a very fast early rise. The afterglow light curves of several other soft bursts showing a plateau or a rising phase may be explained in the framework of this model. The behavior of these bursts shows that there may then be a relation between the softness of the burst and the shape of the early optical light curve of the afterglow.

The optical transient was still fairly bright after ~ 30 d. The late-time evolution of XRF 020903 is well described by the light curve of SN 1998bw, shifted by 0.8 mag (fainter). The other striking feature is the very red SED at 38 d after the burst (~ 31 d in the rest frame). A supernova seems to be the only way to have such a red and curved SED, as other explanations predict a power law for the SED. Assuming for a moment that there is no SN

and that the late-time fading is a power law, it is very surprising that a local supernova, SN 1998bw, would fit the light curve *and* the SED so well. Furthermore, it is a challenge to GRB models to explain how the afterglow could have remained so bright for over 30 days (decaying only by $\sim$ 0.5 mag in 20 days) and be so red. In summary, the existence and brightness of the bump, its timing, and the SED at 38 d, can all be explained naturally by a SN. Adding this to the fact that a spectrum of the OT at 24.6 d strongly resembles a spectrum of SN 1998bw (Soderberg et al. 2005a), there is no doubt that XRF 020903 is associated with a core-collapse supernova.

The global properties of the host galaxy are similar to those of other GRB host galaxies, in the sense that it is subluminous, actively star-forming, and fairly metal-poor. It resembles the host of GRB 031203 (Prochaska et al., 2004; see also Sollerman et al., 2005).

It is unfortunate that the afterglow was not detected at early times. After re-analysis of early data, the announcement of an afterglow at optical and radio wavelengths (Soderberg et al. 2004) came at a time when the host was already dominating the optical flux. This made photometry difficult and most groups stopped taking data. It is conceivable that the afterglow may have been missed at early times because of the presence of the host. Even in the presence of a bright host, it is worth taking data for a long time after the burst, since image subtraction can provide reliable light curves. The X-ray telescope (XRT) on Swift provides positions good enough that the emergence of a supernova in the XRT error box after $\sim$ 2 weeks would pinpoint the location of the host galaxy. GRB 020410 is a perfect example of this strategy (Levan et al. 2005b).

While there is clearly a SN associated with XRF 020903, there are several XRFs where the evidence for a SN is weak, if not lacking altogether. Levan et al. (2005a) and Soderberg et al. (2005a) constrain the brightness of any SN associated with several X-ray flashes, although the lack of measured redshifts for some objects make these constraints less strong than one would wish. XRF 030723 had a strong bump on its light curve (Fynbo et al. 2004) that is interpreted as a SN, akin to SN 1994I, and a SN similar to SN 1998bw can be confidently excluded for that XRF. All this shows that if every XRF has an underlying SN, they have a broad range of peak luminosities (Soderberg et al. 2005a) and light curve shapes. This being said, there is now at least one good example of a classical GRB (e.g. Stanek et al. 2003, Hjorth et al. 2003, Matheson et al. 2003 for GRB 030329), X-ray rich GRB (Stanek et al. 2005, Soderberg et al 2005, for GRB 041006), and X-ray flash (this paper and Soderberg et al., 2005, for XRF 020903) clearly associated with supernovae. This is predicted by theoretical models of stellar collapse (Zhang et al. 2004) and by GRB models where the difference between these various events is explained by a different viewing geometry. All this reinforces the suspicion that XRFs, X-ray rich GRBs, and long GRBs

are slightly different outcomes of the same phenomenon: the collapse of a massive star. The physical mechanisms powering these events appear to be very similar, albeit with a fairly wide variety of observational properties.

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